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Journal of Water Process Engineering 44 (2021) 102400

Contents lists available at ScienceDirect

Journal of Water Process Engineering

journal homepage: www.elsevier.com/locate/jwpe

Safe drinking water for rural communities using a low-cost household system. Effects of water matrix and field testing

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ARTICLE INFO

Keywords:
UVC disinfection
Turbidity
Humic acid
MS2
Drinking water

ABSTRACT

The relationship between turbidity (T) and ultraviolet C (UVC) disinfection is still not clearly understood, as well as no attention has been paid to the contribution of natural organic matter (NOM). The present work assessed the influence of particulate and NOM on the UVC disinfection efficiency in terms of *E. coli* and MS2 removal at bench collimated beam (CB) and flow-UVC systems, both in the laboratory and in the field (Colombia). The flow-UVC reactor was installed as part of a household water treatment (HWT) system consisting of filtration + UVC disinfection. Tests were performed according to the WHO standards using fine test dust, humic acid (HA), and MS2 and *E. coli* as microbiological indicators. CB results showed a significant decrease in the inactivation rate of MS2 in the presence of small concentrations of HA (3.5 mg/L), with killing dose increasing a 65%, vs. non-significant effects of turbidity in the range of 0–20 NTU. Following the same trend, in flow-UVC tests the inactivation efficiency of MS2 decreased solely in the presence of HA. At the same HA concentration and flow rate, an increase in turbidity of 17.6 NTU showed a negligible effect. Conversely, in the presence of HA, UVT_{254} dropped from 88.7% (0 mg/L HA) to 73.3%, reducing MS2 inactivation by 1–2 log-units. Finally, the HWT system could be classified as protective working at flow rates ≤5 L/min. However, in the presence of 3.5 mg/L HA (UVT_{254} < 75%), it presented a limited protection for viruses.

1. Introduction

UVC irradiation was first used for water treatment in 1910 [1]. Despite at that time the use of chemical disinfection was generally extended [2,3], UVC irradiation started to gain more attention due to its effectiveness against all waterborne pathogens including cysts of *Cryptosporidium* and *Giardia* and because of, in contrast to many of the chemical disinfectants, it imparts no taste and odour to the water. In addition, UVC light does not present risk as a result of overdosing or formation of harmful disinfection by-products (DBPs) [4,5].

Research studies on UVC water disinfection are mainly focused on assessing the effective UVC-dose for viruses, bacteria and protozoan inactivation, which have been widely studied and described in the literature [6–16]. These works have shown that while viruses and bacteria spores are the most UVC-resistant pathogens, vegetative bacteria cells and cysts of *Giardia* and *Cryptosporidium* are more susceptible with lower fluence requirements [17,18]. The United States Environmental Protection Agency (USEPA) indicated a required delivery UVC-dose of 40 mJ/cm^2 to deal with most of the viruses and spores [18]. Water quality plays a fundamental role on the UVC disinfection efficiency affecting the transmission of UVC light (UVT) to the target microorganisms [18]. UVT at the wavelength of 254 nm (UVT_{254}) is the main water quality parameter used to define UVC disinfection performance [18]. UVT_{254} is affected by scattering and absorbance of UVC light in water, so that while particulates and colloidal matter shields pathogens from disinfection and scatters light, the dissolved organic fraction absorbs the UVC light as it passes through the water [19].

In continuous flow systems, dose delivery is not only affected by

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https://doi.org/10.1016/j.jwpe.2021.102400
Received 24 June 2021; Received in revised form 8 September 2021; Accepted 19 October 2021
Available online 9 November 2021

water quality, but also by the flow rate, UVC output from the lamp, the UVC light distribution inside the reactor chamber and by the reactor hydrodynamics, which in turn is affected by its dimensions, internal configuration and the flow rate [20]. In centralized treatment plants, for UVC disinfection systems operation, UVC output from the lamp is usually monitored by UVC sensors to measure UVC intensity (UVCI). Two approaches are used for UVC systems operation: the UVCI set point approach, which relies on UVCI readings to change the lamp output in response to changes in UVCI and flow rate [18]; and the calculated dose approach, in which the required UVC-dose is estimated using a dose-monitoring algorithm [18,21] that sets the lamp output to maintain the required dose under varying conditions of flow rate and water quality. However, for point-of-use UVC reactors, usually not equipped with advance monitoring sensors or regulable intensity outputs, flow rate is the utmost importance to maintain the required dose [18]. Lower flow rates allow longer contact time in the reactor and thus higher UVC-doses. Commercial UVC reactors are designed to treat a maximum flow of water, and it is usually listed in the product specification. As well, in the development of new point-of-use reactors, UVC fluence vs. flow rate is usually assessed for the system validation and to define its operation conditions [22–24]. On the other hand, regarding the impact of water quality on UVC efficiency, supplementary treatment process might be required upstream to clarify water and significantly improve UVC inactivation. Such process might include filtration and coagulation to reduce the particulate and organic fraction [18]. Although flow-UVC reactors are widely used, very few works investigate the effect of water quality, from an optical point of view, on UVC disinfection efficiency [25]. In this regard, Hijnen et al. [17] reviewed and compared the results of studies carried out with different water sources under similar conditions (CB tests, strains and UVC-dose) to assess the effect of water quality. From this work, when comparing Oppenheimer et al. [26] and Watercare [27] works which were carried out with the secondary effluent of wastewater treatment plants with studies testing deionized/tap water [6,8,12,15,28–32], a lower inactivation rate was observed in the secondary effluent than in drinking water. In contrast, the comparison of data from Thompson et al. [33] working with secondary effluents showed no inactivation decrease in Poliovirus and Adenovirus when comparing their inactivation in drinking water. In addition, no effects of turbidity, ranging from 0.2 NTU to 5.3 NTU, were observed in Poliovirus and MS2 inactivation in batch conditions [33]. This was recently confirmed by Baldasso et al. [34] who showed non-significant effect of turbidity (0–5 NTU) on MS2 UVC inactivation vs. the critical effect of HA (3.5 mg/L), reducing the inactivation rate of MS2 by 40%. In addition, no synergistic effects between both parameters at those levels were found [34]. Under flow conditions, it was determined that the UVC disinfection performance of MS2 and *E. coli* was not affected for turbidity <30 NTU and total organic carbon (TOC) < 2 mg/L [35,36], while turbidity values up to 80 NTU in deionized water and unfiltered natural water sources (with values ranging from 2.0 to 22.7 NTU) decreased the effectiveness of UVC disinfection as turbidity of the water source increased [37,38]. Moreover, Cheng et al. [39] results, evaluating an individual unit of a photocatalytic membrane reactor equipped with a UVC lamp, showed that the irradiation time to get 5.49 LRV of the bacteriophage f2 increased from 54 s at 0 mg/L of HA to 85 s at 10 mg/L. This was attributed to UVC light absorption by HA.

Up to date, works assessing the performance of HWT systems based on UVC disinfection or proprietary UVC reactors usually report on turbidity [33,35,36,38], but no analysis or investigations are carried out about the complexity of natural water sources which interfere with UVC radiation in the water matrix and may have a critical role on the efficiency of UVC disinfection. Despite turbidity has generally been found to adversely affect UVC treatment as it increases [38], the relationship between turbidity and UVC disinfection is not clearly understood. At this stage, the role of NOM, always present in environmental surface water, has to be also considered as NOM modifies turbidity and certainly absorbs light at the UVC wavelengths [26,39]. This would be of great importance not only for conventional UVC disinfection applications, but also for other emerging water treatment technologies based on the use of UVC, including photocatalysis, UV-H_2O_2 and the use of UV-LEDs. The present work has been developed within the frame of the SAFEWATER project (GCRF-UKRI SAFEWATER project) as part of the design, sizing and performance assessment of a HWT system developed and constructed to treat and provide the daily safe-water needs for a family in isolated communities of developing countries. Technological solutions for safe drinking water have a significant potential to address the SDG-6 set by the sustainable development agenda [40]. In addition, given the huge implications of safe water for public health, food security, poverty reduction and equality, the improvement in water quality and management is directly and indirectly linked to: SDG-1 No poverty, SDG-3 Good Health and Well-being, SDG-5 Gender Equality and SDG-11 Sustainable cities and communities [40].

The WHO International Scheme to Evaluate Household Water Treatment Technologies provides health-based criteria to evaluate household water treatment technologies intended to treat water for microbiological contaminants [41]. It stablishes the characteristics of the water to be tested (chlorine concentration, pH, TOC, T, temperature, total dissolve solids and alkalinity) and the microbiological indicators: *Escherichia coli* (in the group of bacteria), MS2 coliphage and phiX-174 (virus) and *Cryptosporidium parvum* oocysts (protozoa). The WHO Scheme also indicates the organisms pretreatment concentration ($>10^5$/100 mL, $>10^8$/L and $>5{\cdot}10^5$/L, respectively) and the reduction requirement to allow the classification of the technologies as highly protective, protective, or limited protective. The SAFEWATER HWT technology is based on filtration followed by UVC disinfection [41]. The main objective of the present work is to assess the disinfection efficiency of the flow-UVC reactor integrated into the SAFEWATER HWT system against bacteria and viruses, using two indicators *Escherichia coli* and MS2 bacteriophage, in different water quality matrices (varying suspended particulate and NOM concentrations) and operating conditions (flow rate and filtration efficiency prior to disinfection), to ensure it delivers safe drinking water.

2. Methodology

2.1. Research approach

The flow-UVC reactor was tested as part of the HWT system consisting of filtration followed by UVC disinfection, which was designed to provide safe drinking water in rural communities of Mexico and Colombia. To achieve this, firstly the UVC inactivation rate of target microorganisms was assessed through CB tests. The UVC-doses determined were then confirmed in the flow-UVC system at Ulster University facilities (UK) using synthetic water, and in the field in rural communities of Antioquia (Colombia), using natural water sources. For this, the WHO scheme for evaluation of HWT technologies performance [41], was used to determine if the water treatment is either 'highly protective' (4 log reduction value -LRV- of *E. coli* and 5 LRV of MS2), 'protective' (2 LRV of *E. coli* and 3 LRV of MS2) or 'limited protective' when fails to meet the previous criteria.

2.2. Chemicals

Synthetic test water was prepared on the same day of experimentation using A2 fine test dust manufactured by Powder Technology Inc., and humic acid sodium salt (Sigma Aldrich). Test dust is the most used particulate standard to assess filter media and particulate contamination. The particles size and chemical makeup of A2 fine test dust is specified by ISO 12103-1 [42] and its use is recommended by the WHO to simulate turbidity occurring in natural water [43]. On the other hand, HA comprises the largest fraction of the NOM in natural water [44] and it is commonly used to simulate the dissolved organic fraction of natural surface waters. According to WHO HWT performance testing scheme

[41], water matrices with concentrations of 0 and 3.5 mg/L of HA and turbidity levels up to 40 ± 10 NTU were selected to test UVC disinfection efficiency. These chemicals were suspended (test dust) or dissolved (HA) by mechanical stirring in Milli-Q water for all disinfection experiments in the CB and in dechlorinated tap water (left out for 24 h) for flow-system tests in the laboratory.

2.3. Microorganisms growth and enumeration

Escherichia coli and MS2 bacteriophage were used as microbiological indicators to test the efficiency of this technology following the WHO Scheme to evaluate HWT systems performance [41]. MS2, highly UVC-resistant, is generally used as a viral surrogate, while *E. coli* is the most common faecal indicator analysed in drinking water as well as in disinfection studies and protocols. In addition, *E. coli* is the indicator established by the WHO for the verification of the microbiological quality of water intended for human consumption [45]. *Escherichia coli* (ATCC 11229), MS2 (ATCC 155987-B1) and its *E. coli* host (ATCC 15597) were obtained from ATCC®. An overnight culture of *E. coli* ATCC 11229 (concentration of 10^{12} CFU/mL) and a MS2 stock solution (concentration of 10^{12} PFU/mL) were spiked into test water, obtaining an initial concentration of 10^5 CFU/mL for *E. coli* and 10^6 PFU/mL for MS2.

The overnight cultures of *E. coli* ATCC 11229 and *E. coli* host ATCC 15597 were prepared from glycerol master stock solutions stored at −80 °C. First, each strain (from the master stock solutions) was sowing in Chromocult® Coliform Agar (Merck Millipore) plates which were incubated at 36 ± 2 °C for 21 ± 3 h. Then, a single blue colony from each Chromocult plate was transferred to falcon tubes containing 15 mL of tryptone soya broth media (TSB) (Oxoid). The tubes were incubated at 36 ± 2 °C for 12 h in a shaker incubator (200 rpm). Afterwards, the liquid suspension was centrifuged at 4,000 rpm for 5 min. The supernatant was replaced by phosphate borate saline (PBS) solution (Oxoid), obtaining an *E. coli* (ATCC 11229) and *E. coli* host (ATCC 15597) concentration of 10^{12} CFU/mL.

The membrane filtration technique was employed for the detection and enumeration of *Escherichia coli*. Samples were filtered in triplicate through cellulose nitrate membrane filters (0.45 μm) and then transferred to Petri dishes with the suitable growth media (Chromocult® Coliform Agar). Petri dishes were incubated at 36 ± 2 °C for 21 ± 3 h and dark blue to violet colonies were enumerated as *E. coli* with a detection limit of 1 CFU/100 mL.

MS2 was analysed in triplicate following the double-layer agar method [46]. A glycerol stock solution of MS2 kept frosted at −80 °C and an overnight culture of *E. coli* host were used to perform the experiment. For MS2 detection and enumeration, 1 mL of sample and 100 μL of *E. coli* host (from an overnight culture) were poured into Bijou tubes with melted sloppy agar. This was prepared with TSB and bacteriological agar No. 1 (Oxoid). The content of the Bijou tubes was poured into tryptone soya agar (TSA) plates (Oxoid) and then incubated at 36 ± 2 °C for 21 ± 3 h. Lytic plaques were enumerated as MS2 with a detection limit of 1 PFU/mL. Positive controls were performed to ensure stability of MS2 and *E. coli* (ATCC 11229) cultures during the experimental time. For this reason, the working solution of MS2 and *E. coli* (ATCC 11229) was plated at the beginning and at the end of the experiment. The negative controls were prepared as follows: PBS solution, PBS solution and *E. coli* host, MS2 working solution, *E. coli* (ATCC 11229) working solution and water matrix to ensure no material, bacteria, virus and host contamination.

The disinfection efficiency of the target microorganisms was calculated as follow (Eq. 1):

$$LRV = logN_0 - log\ N_t = log_{10}\left(N_0/N_t\right) \quad (1)$$

where LRV represents the log reduction value obtained after a specific UVC irradiation time, N_0 is the microorganisms concentration (CFU or PFU/mL) at the initial time and N_t is the microorganisms concentration (CFU or PFU/mL) at time t.

2.4. Collimated beam tests

Collimated beam (CB) experiments were performed with a 12 W UVC low-pressure mercury lamp (monochromatic at 254 nm) to investigate the effects of turbidity (test dust) and organic matter (HA) on the UVC inactivation of the target microorganisms. Lamp intensity was measured with a spectroradiometer (Ocean Optics Spectroradiometer FLMS 14462), with an operating range from 200 to 800 nm and an optical resolution of 1.5 nm, located at the centre of the surface of the sample, obtaining a value of 0.231 mW/cm^2. The UVC lamp was initially warmed up for 5 min to ensure a relatively stable output. A vessel was placed on the horizontal surface beneath the collimated beam system, constructed following the standard guidelines [47]. It was composed of a 55-cm long cylindric glass tube covered with black paper to assure only vertical incident radiation would arrive to the sample surface and retained vertically in place by a metallic holder. The sample was continuously stirred using a magnetic stirring apparatus and a small stirring bar without creating any vortex while exposing the test solution to UVC light. The solution volume was 100 mL, the vertical path length of the water in the vessel 5.2 cm and the vertical distance from the lamp to the top of the test solution 38 cm.

E. coli response was evaluated in Milli-Q water, while MS2 was assessed at different test dust (turbidity) and HA concentrations. Experiments with MS2 were carried out at three turbidity levels (0, 5 and 20 NTU) and two HA concentrations (0 and 3.5 mg/L) in Milli-Q water (Table 1). Initial concentration of *E. coli* was 10^5 CFU/mL and MS2 was 10^6 PFU/mL. Twelve UVC-dose values were applied between 0 and 320 mJ/cm^2, corresponding to exposure times ranging from 0 to 23 min. Samples (of 1 mL) were collected from the vessel after each exposure time and analysed to determine microorganism concentration.

The effective UVC-dose response was calculated by correcting the measured irradiance as proposed by Bolton and Linden [47], who provided a standardized method to determine UVC-doses in bench-scale collimated beam apparatus reliably and reproducibly (Eqs. (2)–(5)):

$$I_c = E_0 \times F_R \times F_P \times F_W \times F_D \quad (2)$$

$$F_P = \frac{\sum_{i=1}^{12} E_{m,i}/E_{m,C}}{12} \quad (3)$$

$$F_W = \frac{1-10^{-al}}{a \cdot l \cdot ln(10)} \quad (4)$$

Table 1
Description of the main experimental features in terms of water turbidity and HA concentration, flow rate and filtration cartridges conditions for both collimated beam (CB) and UVC-flow system (FS) tests performed in the laboratory.

Test number	Filter cartridge	Turbidity (NTU)	HA (mg/L)
CB-1	–	0	0
CB-2	–	5	0
CB-3	–	20	0
CB-4	–	0	3.5
FS-1	Pristine cartridges	0	0
FS-2	Pristine cartridges	15	3.5
FS-3	Pristine cartridges	40	3.5
FS-4	Pristine cartridges	0	0
FS-5	Pristine cartridges	0	0
FS-6	Pristine cartridges	15	0
FS-7	Pristine cartridges	40	0
FS-8	'Dirty' cartridges	15	3.5
FS-9	'Dirty' cartridges	40	3.5
FS-10	Pristine cartridges	40	3.5

$$F_D = \frac{L}{(L + l)} \quad (5)$$

where I_c is the corrected irradiance (mW/cm^2), E_0 the irradiance reading of the spectroradiometer at the surface centre point of the test solution (mW/cm^2), F_R the reflection factor that corrects for the reflection at the water/air interface (0.975) [47], F_P the petri factor that corrects for the horizontal divergence (0.734) [47], $E_{m,i}$ (mJ/cm^2·s^1) the average incident irradiance at the sample surface at point i, F_W (−) the water factor, a (cm^{-1}) the absorption coefficient, 1 (cm) the vertical path length of the sample, F_D (−) the divergence factor, and L (cm) the distance between the surface of the sample and the UVC lamp. The I_C was calculated for each experimental condition and was used to calculate the effective applied UVC fluence.

In addition, inactivation kinetic data were described by the Chick-Watson linear model [48], a modification of the Chick model. Inactivation kinetic was assessed by observing the microorganisms inactivation at different turbidity values and HA concentrations as a function of the elapsed time of the experiment. The Chick-Watson model is expressed by Eq. (6):

$$log\left(N_t/N_0\right) = -kt \quad (6)$$

where N_0 is the initial microorganism concentration, N_t the concentration of microorganisms (CFU or PFU/mL) at the irradiation time t (min) and k the inactivation rate (min^{-1}). Moreover, Student t-test (confidence level 95%) was applied to determine statistical significant differences between UVC-doses and inactivation rates (k) in different experimental conditions.

2.5. Flow-UVC system tests with synthetic water

A UVC disinfection reactor (UltrARays) equipped with a 16 W low-pressure UVC lamp (Philips), commercially available for drinking water, was used in this study. The reactor was made of stainless steel, with an external diameter of 6.3 cm and 30 cm of length. The lamp sleeve made of quartz was 2.3 cm in diameter and 30 cm of length. The distance from the lamp sleeve to the reactor wall was 2 cm, and the total volume of the reactor 780 mL. The flow-UVC reactor is part of the SAFEWATER HWT system (Fig. 1), where the UVC system was installed after a sedimentation tank (60 L) and a filtration unit and followed by a closed tank (60 L) to safely store treated water. The filtration unit consisted of 2 × 10 in. pleated filters (Finerfilters, UK) of 5 and 1 μm of nominal micron rating. Scanning electron microscope (JEOL, JSM-6010) images of cross sections of the filter elements were taken from pristine cartridges. After water matrices (synthetic test water) preparation in the sedimentation tank, raw water was left for 24 h to allow particles sedimentation simulating the real operation conditions in the field. The UVC lamp was warmed up for 5 min prior to start of testing. The warming up time was obtained based on the spectroradiometer measurements (Ocean Optics Spectroradiometer FLMS 14462) of the output irradiance (at 254 nm) of the lamp against time. According to manufacturer specifications the nominal flow rate of the UVC reactor was 5 L/min. However, due to the quality of the water tested (turbidity + NOM) and the high UVC resistance of MS2, a lower flow rate was also tested. Thus, the system was operated at two different flow rates: 1) 5 L/min using a diaphragm pump (Shurflo 2095–204-112, US) (tests FS-1 to FS-3); and 2) 3.2 L/min using another diaphragm pump (Seaflo SFDP1-012-035-21, China) (tests FS-4 to FS-10). This also helped with the selection of a low-cost pump for its installation in the final SAFEWATER HWT system, which was based on the actual flow rate required by the UVC reactor to meet the WHO standards [41] in the worst water quality conditions. Water samples were taken from the raw water tank (before settling) to measure the initial turbidity of water (sampling point 0, SP0); before (SP1) and after (SP2) the filtration unit to assess turbidity reduction by settling and cartridge filtration; after the UVC reactor (SP3) to assess the inactivation efficiency; and from the treated water tank to check post-treatment contamination (SP4). SP4 samples were kept in the dark at room temperature for 24 h (Fig. 1).

Synthetic test water presented the following characteristics: 0 NTU and 0 mg/L of HA, 15 NTU and 0 mg/L of HA, 40 NTU and 0 mg/L of HA, 15 NTU and 3.5 mg/L of HA and 40 NTU and 3.5 mg/L of HA (Table 1). It was prepared with tap water (Antrim, UK), which was left out for 24 h in the tank for evaporation of chlorine. Chlorine concentration was measured before starting the experimentation using a portable chlorine measurement photometer (eXact® Chlorine Plus).

MS2 and *E. coli* (ATCC 11229) were spiked into test water, given a final concentration of 10^5 CFU/mL for *E. coli* and 10^6 PFU/mL for MS2. Pristine filters and 'dirty' filters (filters with a cake layer of the test dust

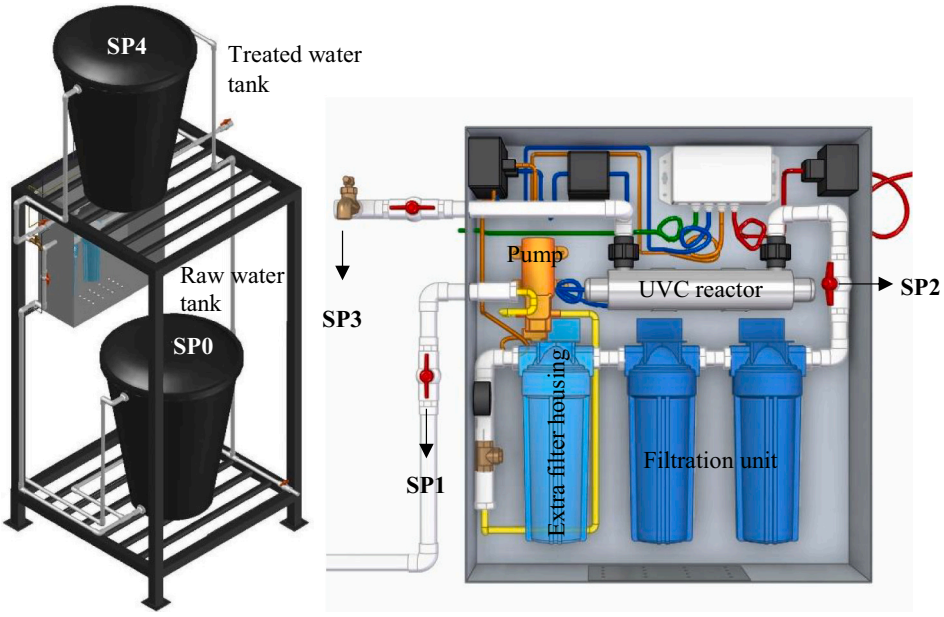

Fig. 1. Diagram of the SAFEWATER HWT system, general view including raw water tank and treated water tanks (left), and detailed filtration and UVC units (right). Sampling points: raw water tank before settling (SP0), before (SP1) and after (SP2) filtration, after UVC (SP3) and treated water tank (SP4).

formed on their outer surface, representing filters after a period of operation) were tested to simulate the worst and optimal removal efficiency of the filtration unit, respectively.

2.6. Field testing in Colombia

Water batches of 10 L were collected from La Miel (6°08′30.8″N 75°34′26.5″W) and Santa Rita (6°13′49″N 75°36′45″W) (Fig. 2a) rivers (Antioquia, Colombia) (sketch map in supplementary materials S.1.1) in clean lid-closed containers, which were stored in the dark at room temperature for preliminary particles sedimentation. Water samples presenting an initial concentration of 10^4 CFU/mL of wild *E. coli* strains and natural organic and inorganic particulate and dissolved compounds, were spiked with MS2 getting an initial concentration of 10^6 PFU/mL. The HWT system tested, presenting the same configuration and features of the HWT system previously described (Fig. 1), consisted of a 16 W UVC lamp (Evans®), a filtration unit made up of two compact spun polypropylene filters of 5 μm and 1 μm (Purikor, Mexico), and 150 L tanks (Fig. 2b). The UVC lamp was warmed up for 5 min and the water was processed through the system at 4.3 L/min by the diaphragm pump Seaflo SFDP1-012-035-21. Nominal flow rate provided by the pump once installed in the HWT systems installed in the field, presenting a flow rate 1.1 L/min higher than in the system tested in the laboratory. A total of 5 tests were performed in the field, 2 using water from La Miel river (FT -field test- 1 and FT-2) and 3 from Santa Rita river (FT-3, FT-4 and FT-5). Samples were taken from SP1 and SP4 for T (HACH 2100Q), UVT_{254} (Genesys ThermoFisher) and TOC (Shimadzu 5264 TOC-VCPH) analysis and *E. coli* and MS2 enumeration (see Section 2.3).

2.7. Water analysis

Turbidity (T) and transmittance at 254 nm (UVT_{254}) were measured using a turbidimiter (Hanna, HI-93703) and a UV/VIS spectophotometer (Jenway 6305), respectively. HA concentration in water was prepared by weighing HA and then TOC was measured by means of a TOC (mg/L) – Absorbance (−) reference curve at the wavelength of 254 nm which was defined by plotting TOC and absorbance values of 10 HA solutions (1, 2, 3, 4, 5, 10, 20, 30, 40 and 50 mg/L). Reference TOC measurements were measured by a Shimadzu TOC-5000 Analyzer. At the CB set up, T, UVT_{254} and TOC were measured before UVC exposure started, while microbiological analyses were carried out before and after a specific UVC irradiation time. In flow-system tests, T was measured for the synthetic test water before settling (SP0) and before (SP1) and after (SP2) the filtration unit, while UVT_{254} and TOC were measured before the UVC lamp (SP2). Microbiological analyses were performed in water samples before filtration (SP1), before (SP2) and after (SP3) the UVC lamp and for the treated water tank (SP4).

The UVC fluence of the flow system, or UVC irradiance per surface area (mW/cm^2), was determined by KI-iodate actinometry [49], which determines the irradiance in the photoreactor at 254 nm. Detailed description of the actinometry method and calculations is reported in the supplementary materials (S.1.2). The fluence at 254 nm was 5.2 mW/cm^2.

3. Results and discussion

3.1. Collimated beam tests results

MS2 inactivation kinetics at different tested T and HA concentrations are shown in Fig. 3. The Chick-Watson model showed a statistically significant fitting between the experimental data at all evaluated conditions, this is a linear decay of MS2 concentration as a function of the UVC exposure time for all T and HA values. The disinfection rate (k) decreased from 0.27 (± 0.02) min^{-1} at 0 NTU and 0 mg/L of HA to 0.17 (± 0.01) min^{-1} at 0 NTU and 3.5 mg/L of HA, indicating a decrease in the UVC disinfection efficiency (Student t-test p value of 0.004). No statistically significant differences were observed in MS2 inactivation rate in the absence of HA when increasing turbidity levels from 0 to 20.4 (± 0.5) NTU (Student t-test p value of 0.111). From Fig. 3, it can clearly be observed a MS2 removal of 4 LRV after 15 min of UVC treatment, and while not significant differences were observed at different turbidity levels with required exposure times ranging from 13 to 15 min, when 3.5 mg/L of HA were in water, a maximum removal of 3.72 (±0.14) LRV was achieved after 20.3 min. As expected, *E. coli* was much more sensitive to UVC, attaining 4 LRV within 2.8 min (k of 1.13 ± 0.05 min^{-1}) in Milli-Q water. Microbiology control results showed stability of *E. coli* and MS2 cultures over the experimental time, as well as no material, bacteria, virus and host contamination was found in all tests performed.

The UVC-dose required to produce a 4 LRV of MS2 in Milli-Q water (0 NTU) was 108 mJ/cm^2, while little differences in the killing dose were found when turbidity increased to 4.7 (±0.5) NTU (60 mJ/cm^2) and 20.4 (±0.5) NTU (80 mJ/cm^2) (Fig. 4). However, in the case of HA concentration, the effect was more pronounced. For 3.5 mg/L of HA in clear water (0 NTU) the UVC killing dose for 4 LRV increased a 65% (up to 177 mJ/cm^2) in relation to the absence of HA. On the other hand, *E. coli* reached 4 LRV after 21 mJ/cm^2 UVC dose (Fig. 4). This initial finding indicated the strong detrimental effect of few mg/L of HA on UVC disinfection efficiency compared with the much lower effect of turbidity, in the range 0–20 NTU the dose necessary to attain MS2–4 LRV decreased by a 20%.

Fig. 2. a) Natural water sampled in La Miel river located in Antioquia (Colombia); and b) real scale SAFEWATER HWT system installed at household level in a rural community of Antioquia.

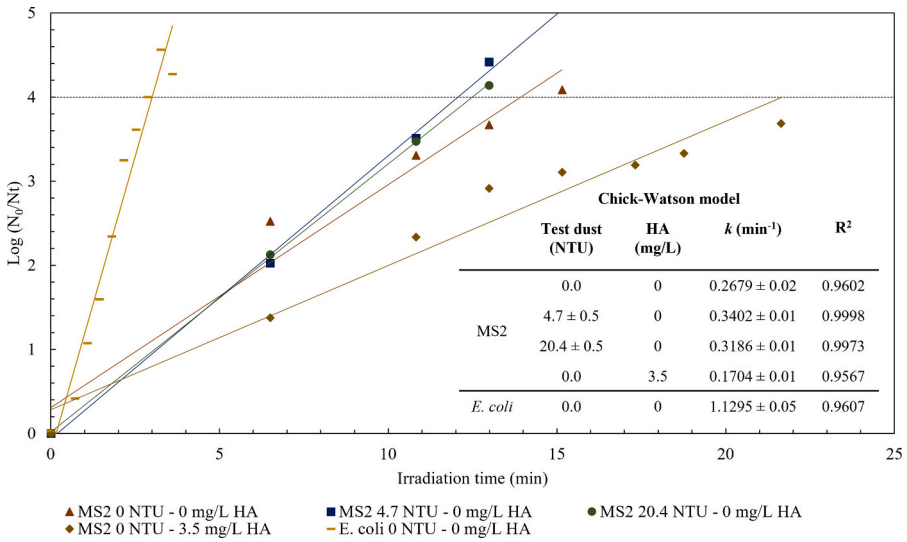

Fig. 3. *E. coli* and MS2-UVC-inactivation kinetics (dots) determined in the CB at different T and HA values, and Chick-Watson linear model fitting (lines), inactivating rate (k) and least square coefficient (R^2).

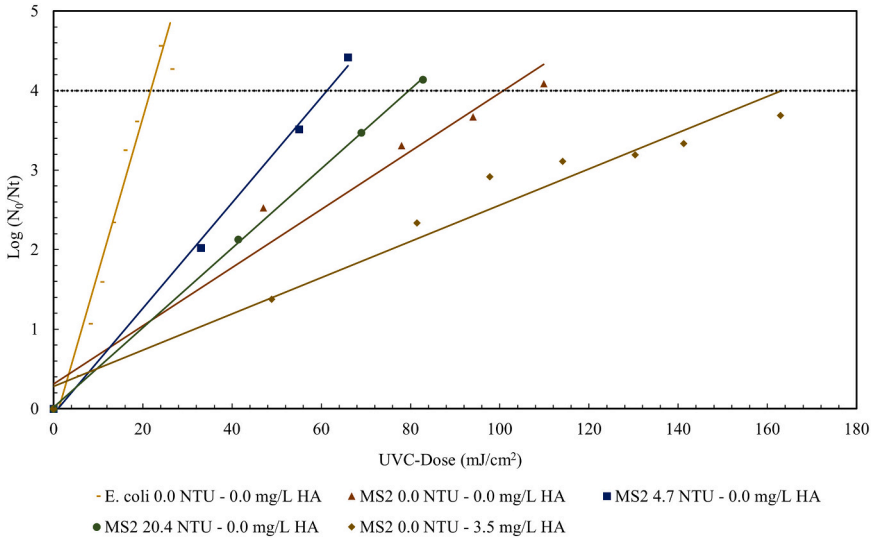

Fig. 4. UVC-dose response of *E. coli* and MS2 (dots) determined in the CB at different turbidity and HA conditions, including the linear least-square fittings (lines).

3.2. Flow-UVC experiments with synthetic water

Table 2 shows the main results obtained from the experiments performed under flow conditions. The settling process allowed a maximum particles removal of 30.4 (±1.52) %. Regarding the filtration unit, it was observed that 'dirty' filters achieved 100% turbidity removal for all turbidity levels tested, whereas the removal efficiency of pristine filters was lower, with an average of 15.2%. MS2 and *E. coli* concentration did not decrease during filtration neither in pristine nor 'dirty' filters. *E. coli* has a diameter of 1 μm and 0.5–2 μm length and MS2 is of 24 nm of diameter, making them difficult to remove by physical methods, such as filtration by commercial cartridge filters. Although the second filter was rated 1 μm by the manufacturer, no microorganisms removal was observed, even when the filter was covered with fine test dust particles. From scanning electron microscope images of pristine pleated filters (Supplementary materials, S.2.1), no significant differences in the pore structure were observed, only the thickness of the filter media was different being the 5 μm thicker than the 1 μm filter element. The performance of the filtration unit of the HWT system developed within the framework of the SAFEWATER project has been reported by Afkhami et al. [50].

In the flow-UVC system, the UVC-dose ranged from a minimum of 47.2 mJ/cm^2 to a maximum of 64.8 mJ/cm^2 at 5 L/min and from 79.2 mJ/cm^2 to 98.2 mJ/cm^2 at 3.2 L/min. >5 LRV reduction was achieved for *E. coli* regardless of the flow rate, T or HA levels in water as the final *E. coli* concentration was below the detection limit (BDL) in all cases (Table 2, Fig. 5a). However, under the same conditions, 5 LRV of MS2 was never reached. Its reduction varied from a minimum of 1.55 (±0.58) LRV to a maximum of 3.72 (±0.14) LRV. In the absence of HA, with average UVT_{254} of 88.7%, 3.33 (± 0.12) - 3.72 (±0.14) LRV were achieved when working at 3.2 L/min (UVC-doses of 84.4–96.4 mJ/cm^2), with a minimum of 2.52 (±0.18) LRV at 5 L/min (UVC-dose of 64.8 mJ/cm^2). Moreover, nor *E. coli* neither MS2 re-growth were observed in treated water stored in the dark at room temperature for 24 h.

As expected, under the same conditions of water quality (T, HA, and initial MS2 concentration) the decrease in flow rate, and thus the UVC-dose increase, i.e. increase residence time and hence increased UVC-dose, resulted in a higher virus inactivation. On the other hand, for 3.5 mg/L of HA, MS2 removal varied from 1.62 (±0.51) to 2.02 (±0.55) LRV. UVT_{254} dropped to 73.3% on average and UVC-dose dropped

Table 2
Summary of main water characteristics, UVC-dose and MS2 and *Escherichia coli* LRV under UVC light for the set of flow laboratory (FS) and field tests (FT) performed.

Test number	Turbidity (NTU)[a]	Turbidity (NTU)[b]	Turbidity removal (%)	TOC (mg/L)	UVT_{254} (%)	UVC-dose (mJ/cm^2)	MS2 (PFU/mL)			*E. coli* (CFU/mL)		
							Initial	Final	*LRV*	*Initial*	Final	*LRV*
FS-1	0.0	0.0	–	0.06 ± 0.006	95.9 ± 1	64.8	(2.1 ± 0.3) 10^6	(6.3 ± 2.0) 10^3	2.52 ± 0.18	(1.3 ± 0.2) 10^5	BDL	5.13 ± 0.15
FS-2	11.2 ± 0.5	10.5 ± 0.5	3.2 ± 0.2	1.23 ± 0.01	71.6 ± 1	48.4	(1.2 ± 0.4) 10^6	(1.4 ± 0.2) 10^4	1.91 ± 0.21	(1.3 ± 0.7) 10^5	BDL	5.12 ± 0.54
FS-3	22.3 ± 0.5	19.7 ± 0.5	6.2 ± 0.3	1.34 ± 0.01	69.8 ± 1	47.2	(1.7 ± 0.7) 10^6	(1.5 ± 0.2) 10^4	2.02 ± 0.55	(1.4 ± 0.08) 10^5	BDL	5.15 ± 0.01
FS-4	0.0	0.0	–	0.18 ± 0.002	93.0 ± 1	98.2	(1.7 ± 0.3) 10^6	(5.5 ± 0.6) 10^2	3.54 ± 0.29	–	–	–
FS-5	0.0	0.0	–	0.26 ± 0.003	91.3 ± 1	96.4	(2.2 ± 0.005) 10^6	(5.1 ± 0.7) 10^2	3.72 ± 0.14	–	–	–
FS-6	10.1 ± 0.5	4.9 ± 0.5	34.7 ± 1.7	0.62 ± 0.006	83.4 ± 1	88.0	(2.3 ± 0.07) 10^6	(5.0 ± 1.0) 10^2	3.64 ± 0.23	–	–	–
FS-7	21.7 ± 0.5	14.0 ± 0.5	25.6 ± 1.3	0.78 ± 0.008	80.0 ± 1	84.4	(1.2 ± 0.1) 10^6	(5.4 ± 0.2) 10^2	3.33 ± 0.12	–	–	–
FS-8	11.6 ± 0.5	0.0	100	0.81 ± 0.008	79.6 ± 1	84.0	(2.4 ± 0.2) 10^6	(5.8 ± 2.0) 10^4	1.62 ± 0.51	(8.6 ± 0.9) 10^4	BDL	4.93 ± 0.10
FS-9	23.2 ± 0.5	0.0	100	0.77 ± 0.008	80.3 ± 1	84.8	(1.2 ± 0.4) 10^6	(3.2 ± 0.8) 10^4	1.55 ± 0.58	(1.5 ± 0.1) 10^5	BDL	5.17 ± 0.06
FS-10	19.9 ± 0.5	17.6 ± 0.5	6.1 ± 0.3	1.04 ± 0.01	65.0 ± 1	79.2	(1.2 ± 0.4) 10^6	(2.6 ± 0.3) 10^4	1.83 ± 0.49	(1.1 ± 0.6) 10^5	BDL	5.06 ± 0.54
FT-1	3.5 ± 0.4	0.7 ± 0.04	79.4 ± 4.0	0.07 ± 0.0007	95.7 ± 0.6	75.2	(1.1 ± 0.1) 10^6	(4.4 ± 4.7) 10^1	4.63 ± 0.56	(3.7 ± 0.9) 10^4	BDL	4.57 ± 0.35
FT-2	2.9 ± 0.5	1.0 ± 0.4	65.5 ± 3.3	0.07 ± 0.0007	95.7 ± 3.0	75.2	(4.8 ± 1.9) 10^6	(4.8 ± 1.3) 10^1	5.08 ± 0.35	–	–	–
FT-3	6.8 ± 1.6	1.7 ± 0.4	75.0 ± 3.8	1.36 ± 0.01	69.2 ± 1.7	54.4	(1.1 ± 0.07) 10^6	(3.7 ± 1.9) 10^2	3.51 ± 0.28	(4.2 ± 0.8) 10^4	BDL	4.62 ± 0.24
FT-4	3.5 ± 0.9	1.2 ± 0.5	65.7 ± 3.3	0.39 ± 0.004	88.3 ± 2.5	69.4	(1.5 ± 0.2) 10^6	(7.9 ± 6.0) 10^2	3.47 ± 0.61			
FT-5	2.7 ± 0.5	0.9 ± 0.13	67.0 ± 3.4	0.24 ± 0.002	91.5 ± 3.7	71.9	(5.3 ± 1.1) 10^6	(3.0 ± 2.4) 10^2	4.35 ± 0.39			

[a] Turbidity before the filtration unit (SP1).
[b] Turbidity after the filtration unit/before the UVC reactor (SP2); BDL: below the detection limit.

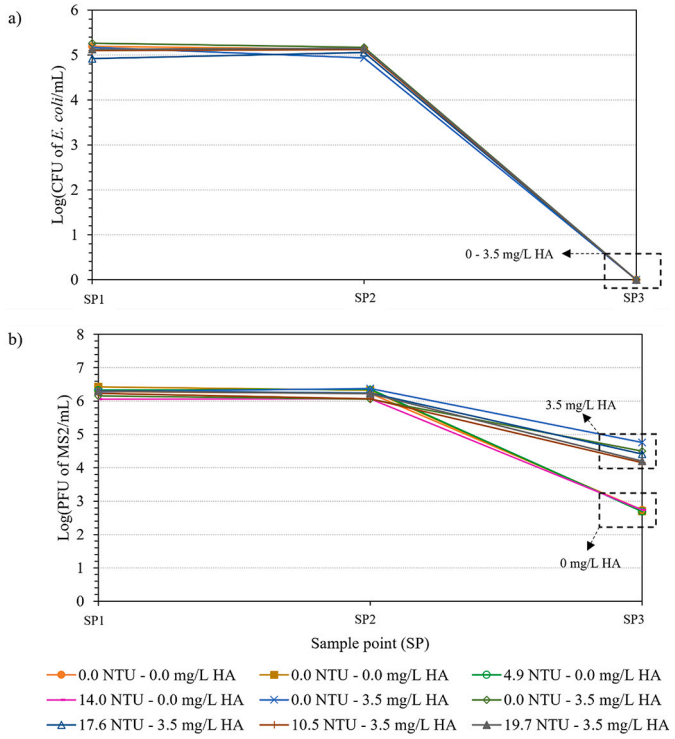

Fig. 5. UVC inactivation of *E. coli* (a) and MS2 (b) at different T and HA values in the flow-UVC system at 3.2 L/min. Sampling points: SP1 - before filtration, SP2 – after filtration and before UVC lamp, and SP3 – after the UVC-flow reactor.

between 13.7% to 27.2%, with UVC-doses ranging from 47.2 to 84.8 mJ/cm^2. As result, MS2 reduction was 1–2 log-units lower than in the absence of HA.

UVC-dose response does not follow a clear trend since under flow conditions, UVC-dose distribution inside the reactor is not only affected by water quality (T + HA), but also by the reactor hydrodynamics and the radiation distribution in the UVC photo-reactor. However, the effect of water quality could be assessed from tests performed using reactors of exactly same characteristics (in terms of power, configuration and dimensions) and flow rate. So that, when turbidity concerned, at the same HA concentration and flow rate, an increase in turbidity from 0 to 9.1 (±0.5) or 17.6 (± 0.5) NTU showed a negligible effect on the UVC disinfection efficiency. Test FS-2 (Table 2) was performed at 5 L/min, 3.5 mg/L of HA and 13.7 (±0.5) NTU, while test FS-3 was performed at 5 L/min, 3.5 mg/L of HA and 19.7 (±0.5) NTU, getting 1.91 (±0.21) and 2.02 (±0.55) LRV, respectively. Tests FS-6 and FS-7 were carried out at 3.2 L/min, 0 mg/L of HA and 4.9 (±0.5) and 14 (±0.5) NTU achieving 3.72 (±0.14) and 3.33 (±0.12) LRV. The same trend was observed comparing tests FS-8, FS-9 and FS-10. These tests were carried out at 3.2 L/min, 3.5 mg/L of HA and 0, 0 and 17.6 (±0.5) NTU achieving 1.55 (±0.58), 1.62 (±0.51) and 1.83 (±0.49) LRV, respectively. Fig. 5b demonstrates the clear different impact of the two parameters, where small concentrations of HA (0–3.5 mg/L) have a greater effect over MS2 removal performance than those of turbidity (0–20 NTU) changes. It can be clearly seen that the inactivation of MS2 depends on the presence or absence of HA, measured through UVT_{254}, since it remains practically unchanged with varying turbidity levels in water.

3.3. Field tests results

Results from field testing are summarized in Table 2. The initial

turbidity of water from La Miel ranged from 2.9 (±0.5) NTU to 3.5 (±0.4) NTU, while from Santa Rita river ranged from 2.7 (±0.5) NTU to 6.8 (±1.6) NTU. With an average particle removal of 70.5%, turbidity levels after filtration were below 1.0 (± 0.4) NTU and 1.7 (± 0.4) NTU, respectively. The highest UVT_{254} values were found in La Miel with 95.7%, corresponding with 4.63 (± 0.56) LRV and 5.08 (± 0.35) LRV of MS2. In Santa Rita river, with the lowest UVT_{254} value of 69.2%, MS2 inactivation dropped to 3.51 (±0.28) LRV. *E. coli* concentration was always BDL (>4.5 LRV) and MS2 reduction was always >3 LRV.

3.4. Discussion

Previous works have reported a UVC fluence ranging from 1 to 9 mJ/cm^2 for *E. coli* inactivation [6–8,10,14,28], requiring a UVC-dose of 8.4 mJ/cm^2 for 4 LRV. A range of 5–139 mJ/cm^2 was indicated for MS2 inactivation [9,10,12,13,15,16] with dose values of 16 mJ/cm^2, 34 mJ/cm^2, 52 mJ/cm^2 and 71 mJ/cm^2 corresponding to 1, 2, 3 and 4 LRV. This is in agreement with our results, where MS2 showed higher resistance to UVC disinfection than *E. coli*. However, the doses obtained in our study were slightly higher than previously published, with required 108 mJ/cm^2 (MS2) and 21 mJ/cm^2 (*E. coli*) to attain 4 LRV in Milli-Q water. This could be due to the higher corrected UVC dose values considered for the inactivation experiments, which ranged from 0 to 320 mJ/cm^2 compared to those used in past studies [6,8–10,12–16,28]. At full scale flow conditions, UVC-dose always exceeded the minimum of 40 mJ/cm^2 for drinking water treatment recommended by the USEPA [18]. However, it was not enough to get the same inactivation level for MS2.

The water optical properties in the UVC region of the spectrum are of huge importance to understand and explain the disinfection results in the presence of dissolved organics (NOM and/or HA) and suspended inorganic matter (turbidity). According to previous authors [35], turbidity and UVC transmittance are the most important water parameters in UVC disinfection. UVC transmittance is directly affected by the presence of light absorbing compounds including mainly NOM, usually dissolved among other chemicals [51]. HA together with fulvic acids, are the main constituents of NOM, which strongly absorb UVC and visible radiation and colour natural water resources [52]. It is reported that HA small concentrations (<3.5 mg/L) in water may absorb more than the 80% of the UVC radiation [53]. On the contrary, turbidity agents –i.e. organic or inorganic particulate matter– just scatter the light shielding the microorganisms and occasionally absorb UVC radiation, reducing the UVC dose delivered over the microbial [54].

Previous articles report on the effect of turbidity of MS2 UVC inactivation showing non-significant effect over the dose for turbidity below 30 NTU [34,35,55], but lower inactivation was reported with turbidity values up to 80 NTU in deionized water [37]. This is in agreement with our work, where in both experimental systems, CB and flow-UVC with the same water characteristics -HA concentration and microorganisms load- and flow rate, turbidity up to 20.4 (± 0.5) NTU slightly affected the inactivation efficiency of MS2.

Regarding HA, it has been found as the most important factor to influence the killing UVC-dose [34,39,53]. On average, in the presence of 3.5 mg/L of HA in synthetic water, UVT_{254} values were of 73.3% resulting in 1.7 LRV of MS2 vs. 3.35 LRV in the absence of HA (UVT_{254} of 88.7%). Field tests showed a reduction of 1.2 log-units on MS2 inactivation when UVT_{254} dropped from 95.7 (±0.6) % to 69.2 (±1.7) %. Younis et al. [36] tested a proprietary UVC reactor showing a reduction of 4.2 log-units on MS2 inactivation when artificially reducing the UVT_{254} of water from 95% to 70%, while the disinfection capacity of the system was not significantly impacted by turbidity values ranging from 0 to 18 NTU. Recently, Baldasso et al. [34] claimed the critical role of dissolved NOM and the irrelevant influence of turbidity on UVC disinfection, for UVC transmittances above 77% and turbidity values under 5 NTU. Our results are in perfect agreement with these findings. In addition, some works have studied the UVC disinfection efficiency in natural waters just taking turbidity into consideration [35,37,38], when natural waters, and especially surface waters, are the results of a complex matrix of suspended and dissolved organic and inorganic matter. So, it might result in a limited interpretation of the contribution of turbidity to UVC disinfection. In our study, in both experimental configurations, the differences in the inactivation efficiency relied on the presence/absence of HA in water, directly affecting the UVC required dose and thus the inactivation efficiency, while turbidity slightly affected. Finally, in order to confirm laboratory results and to assess the performance of the HWT system under real operation conditions, field tests were also performed at household level in rural communities of Colombia, using natural water sources. Regarding the filtration unit, with maximum turbidity levels of 22.3 (± 1.6) NTU after sedimentation in laboratory testing, effluent turbidity only reached the WHO HWT criterion of <5 NTU [45] for 'dirty' filters. Its efficiency improved over time as a cake built up on its surface [50]. On the other hand, in field testing using spun filters and with maximum turbidity levels of 6.8 (± 1.6) NTU, effluent turbidity always met the WHO recommended threshold (5 NTU). However, pleated filters can be washed and reused several times without affecting its performance [50], significantly reducing the cost and improving sustainability of the HWT system. In addition, same trend was observed in UVC inactivation in both laboratory and field tests: *E. coli* was always BDL regardless of the water quality, strain and flow rate (3.2–5 L/min); and >3 LRV of MS2 was achieved when UVT_{254} > 75%. Thus, the HWT system was able to meet the WHO reduction requirements [41] not only in the laboratory, but also in field testing natural water sources with natural particulate, dissolve organic and inorganic matter, and wild bacteria strains. Even in the worst water quality condition tested in the field (Santa Rita river), UVT_{254} of 69.2 (±1.7) % and T of 6.8 (±1.6) NTU, the system was able to achieve a 'protective' level of 3.51 (±0.28) viral LRV.

4. Conclusions

The results of this research clearly demonstrated the following:

(1) Despite the detrimental effect of NOM on UVC disinfection efficiency is well known, the performance assessment of HWT systems based on UVC disinfection or proprietary UVC reactors is usually based on turbidity, but no analysis or investigations are carried out about the complexity of natural water sources which interfere with UVC radiation in the water matrix and may have a critical role on their efficiency. What is more, works studying the UVC inactivation efficiency in natural water generally just monitor turbidity, ignoring the complexity of natural water sources which might result in a limited interpretation of the contribution of turbidity to UVC disinfection.

(2) Despite turbidity has generally been found to adversely affect UVC treatment as it increases, the disinfection efficiency decreased solely in the presence of HA, due to the absorption of UVC at 254 nm by HA molecules, while turbidity of 20.4 (±0.5) NTU did not have a significant effect on UVC inactivation.

(3) The collimated beam tests in Milli-Q or tap water could not be extrapolated to flow-UVC systems operating with natural water sources. The NOM results showed a strong detrimental effect on UVT_{254} reducing the effectiveness of UVC disinfection. Therefore, water quality should be considered before application of UVC.

(4) The effect of T and HA concentration on UVC disinfection efficiency followed the same trend in both experimental configurations, collimated beam and flow system. Therefore, the collimated beam results can be used as a preliminary step for the design of flow-UVC reactors.

(5) 5 LRV of MS2 was rarely reached in the conditions of this study (maximum dose delivered 177 mJ/cm^2), even though the recommended minimum UVC-dose of 40 mJ/cm^2 to operate UVC disinfection systems set by the USEPA was always exceeded.

Thus, 40 mJ/cm^2 might be not sufficient to inactivate UVC-resistant microorganisms as viruses and bacteria spores.

(6) Field results confirmed the good performance of the HWT system, following both laboratory and field tests the same trend in terms of turbidity removal (15.2% and 100% corresponding with pristine and 'dirty' pleated filters in the laboratory and 70.5% for 'dirty' spun filters in the field), and *E. coli* (always BDL regardless of the water quality, flow rate and strain) and MS2 (>3 LRV for $UVT_{254} > 75\%$) inactivation.

(7) Regarding the WHO scheme for evaluation of HWT systems performance and the set of tests performed, the system under evaluation could be classified as highly protective and protective (high pathogen removal) for bacteria and viruses when working at flow rates ≤5 L/min. From laboratory testing using synthetic water, in the presence of 3.5 mg/L of HA ($UVT_{254} < 75\%$), it presented a limited protection for viruses.

The findings presented in this work resulted from the laboratory testing following the WHO criteria of performance for this HWT system consisting of filtration and UVC disinfection designed to provide safe drinking water in rural Mexico and Colombia. However, regarding the extended use of UVC for drinking water disinfection, and the limited number of works addressing the effects of both suspended particulate and NOM, further research to define the parameters affecting the UVC disinfection performance of potable water is still needed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study is part of SAFEWATER projects supported by Global Challenges Research Fund (GCRF) UK Research and Innovation (SAFEWATER; EP-SRC Grant Reference EP/P032427/1).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2021.102400.

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